Image from NASA:
https://commons.wikimedia.org/wiki/File:Earth_Western_Hemisphere_transparent_background.png#filelinks

Geospatial Problem Solving

Surface Hydrologic Analysis

AmericaView
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This module provides even more examples of raster analysis methods. Here, we will focus on modeling surface hydrology.

Module Topics

1. Pit filling/hydrologic correction
2. Flow direction
3. Flow accumulation
4. Synthetic stream networks
5. Stream link and order
6. Pour points and watersheds

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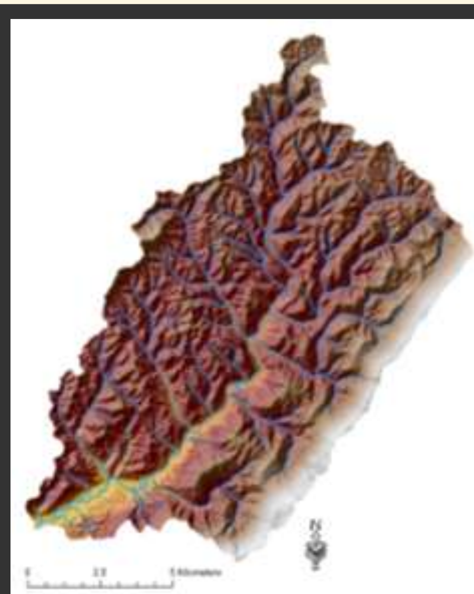
These are the topics covered in this module.

Watersheds



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A watershed or drainage basin represents all the land area that drains to a specific stream.

Watersheds are nested, so smaller watersheds combine to form larger drainage basins.

For example, the Horseshoe Run watershed is within the Upper Cheat Watershed, which is in the Cheat Watershed, which is in the Mon River Watershed, which is in the Ohio river drainage basin.

In this module, you will learn how to produce stream networks and watershed boundaries from just digital elevation data.

Surface Hydrologic Modeling

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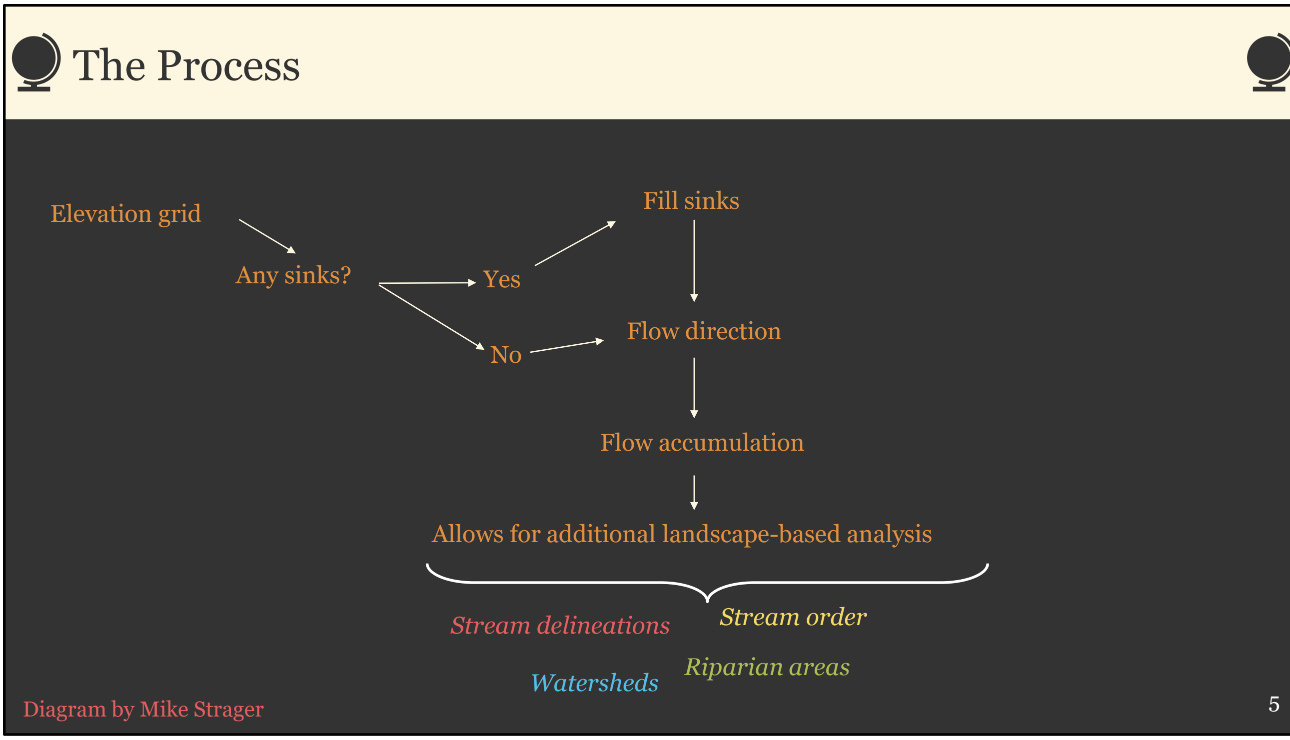


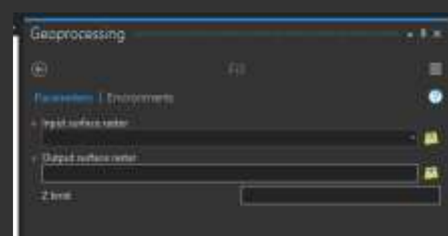
This diagram highlights the process that is used to perform hydrologic analysis.

We will step through this process in the following slides.

Fill Sinks

- Depressions in the DTM where water gets trapped
- A sink prohibits calculating future flow direction grid values.
- A sink occurs when all neighboring cells are higher than the processing cell.
- Sometimes they are natural features!
- Input= DEM

112	111	110
113	108	110
112	112	112



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The required input to a surface hydrologic modeling workflow is a digital terrain model (DTM).

The first task is to fill sinks. Sinks represent depressions in the landscape that hinder the flow of water over the landscape.

In order to perform surface hydrologic analysis, we need to be able to model the flow of water from the ridge to the valley.

So, if water gets trapped in a local depression, this is an issue. A sink prohibits calculating future flow direction values, and they occur when all neighboring cells are higher than the cell being processed, as demonstrated in the provided example.

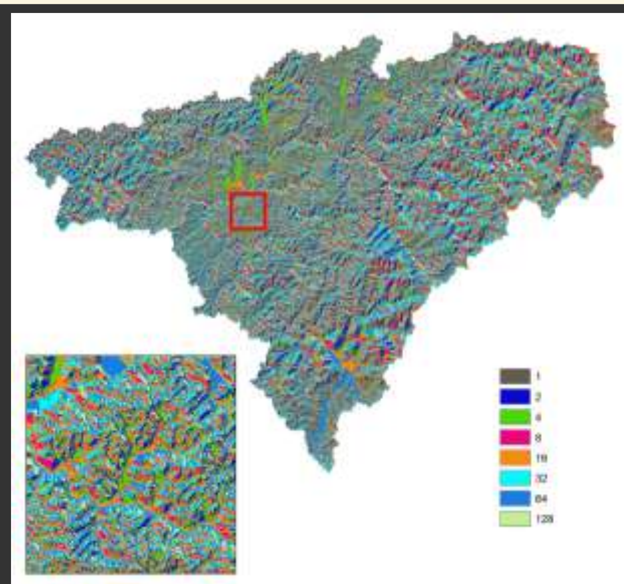
Sometimes sinks represent errors or artifacts from creating the data. Sometimes they represent real features on the landscape. Regardless, sinks must be filled to perform the analysis. A generalized representation of the terrain is required.

The required input is a DEM or DTM. Once sinks have been filled, the result is a hydrologically corrected DEM.

Flow Direction

- Created from an elevation surface
- Direction values are assigned
- Flow direction grids are used in many hydro GIS functions
- Input = Filled DEM

32	64	128
16		1
8	4	2



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Flow direction represents the direction of flow from a center cell to its neighbors.

Flow will progress to the cell with the greatest downhill slope in comparison to the center cell.

The 3-by-3 window provided here shows the codes used to indicate different flow directions.

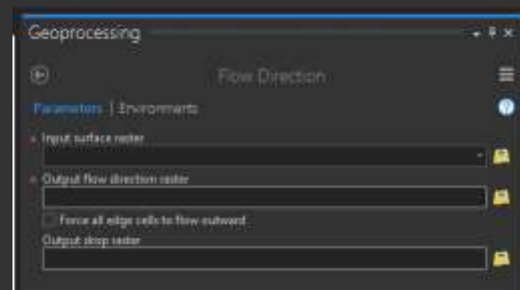
For example, a code of 16 suggests that water will flow to the cell to the left.

The required input for a flow direction calculation is a filled or hydrologically corrected digital terrain model (DTM).

This example relates specifically to the D8 method. Other methods are available to calculate flow direction, as will be discussed later.

Flow Direction

- Created from an elevation surface
- Direction values are assigned
- Flow direction grids are used in many hydro GIS functions
- Input = Filled DEM
- Can force edge cells to flow outward



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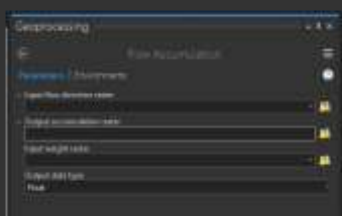
Note that you can force edge cells to flow outward relative to the DEM extent.

Flow Accumulation

- Accumulated flow = number of cells flowing into each cell in the output grid. Current processing cell is not considered in this accumulation.
- Output cells with a high flow accumulation are areas of concentrated flow and may be used to identify stream channels.
- Output cells with a flow accumulation of zero are local topographic highs and may be used to identify ridges
- Input = Flow direction grid



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Flow accumulation represents the number of cells that flow into the current cell, not including the current cell.

Output cells with a high flow accumulation are areas of concentration of flow and may be used to identify stream channels.

Output cells with a flow accumulation of zero are local topographic highs and may be used to identify ridges.

A flow direction raster grid is a required input for flow accumulation calculations.

Calculations from a flow accumulation grid

Estimating Drainage Area

Flow Accumulation Value X Cell Area X Required Conversion Factors

Estimating Discharge

Discharge = Volume of Water / Unit Time (ft^3/s, cm^3/s, etc.)

$$\frac{\textit{Flow Accumulation 1}}{\textit{Discharge 1}} = \frac{\textit{Flow Accumulation 2}}{\textit{Discharge 2}}$$

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Flow accumulation values represent the number of cells flowing into the processing cell. They do not represent a contributing or drainage area.

If you would like to calculate drainage area you will need to multiply the flow accumulation value by the cell size. You can then use conversion factors to convert to other area units.

For example, if 812 cells flow into a processing cell and the cell size is 15-by-15 meters, then the contributing area would be calculated as 812 times 15 times 15, or 182,700 square meters. You can then convert to other area units, such as hectares or acres, using the necessary conversion factors.

Discharge represents the volume of water passing a point in a given amount of time. Units of measurements include cubic feet per second and cubic centimeters per second.

Discharge can be roughly estimated from flow accumulation using the ratio method by comparison to a location of known discharge.

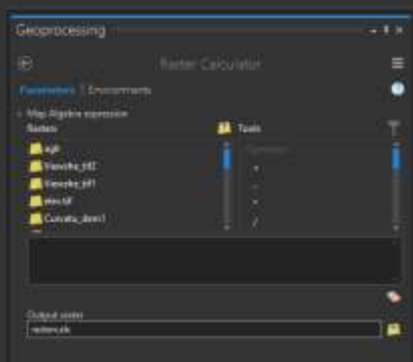
For example, if discharge is measured at a gauging station and flow accumulation is calculated using surface hydrologic modeling methods, then discharge can be estimated using the flow accumulation at another location.

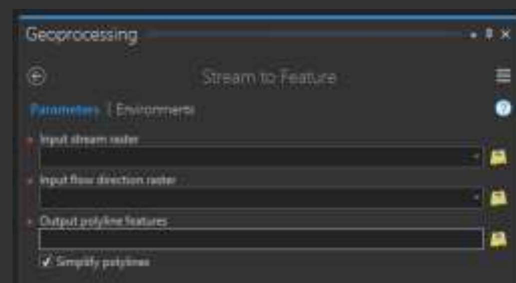
Although this method allows for an estimate of discharge from flow accumulation, it is generally considered a rough measure, as there are many factors that this simple ratio method does not take into account. For example, this method does not take into account variability in topographic slope, stream channel morphology, watershed shape, soil characteristics, and land cover. All these factors could impact stream discharge.

Even given the limitations, this method can provide a useful estimate.

Defining Streams

❖How much flow accumulation is required to create a stream?





Input = Flow accumulation grid

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Once a flow accumulation surface is generated, it is possible to generate a synthetic stream network.

A threshold value must be defined in terms of flow accumulation. All cells with a flow accumulation higher than this value will be coded as a stream. All other cells will be coded as not a stream.

This calculation can be performed using Raster Calculator. So, the calculation is fairly easy.

The complexity is determining an adequate threshold value.

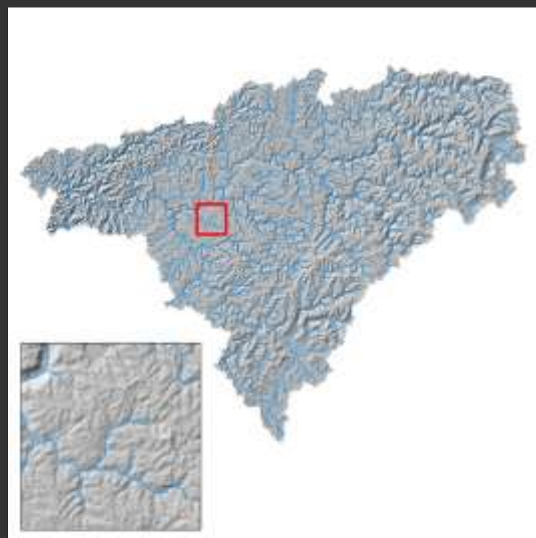
How much flow accumulation is required to create a stream? The answer to this question can depend on many factors including how the stream is initiated, soil conditions, terrain characteristics, and land cover. So, there is no correct answer.

The goal is to pick a value that provides a stream network that is adequate for the analysis purposes.

In West Virginia, we commonly use a flow accumulation value corresponding to a contribution areas of 200 acres.

Once a synthetic stream network is generated, the raster data can be converted to vector line features. Simplification can be applied if desired.

Synthetic Stream Network



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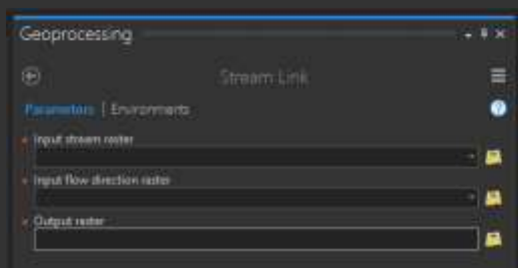
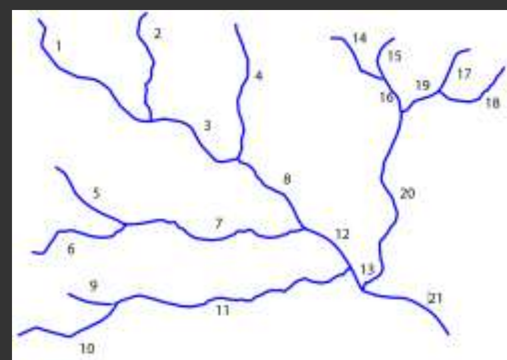
This slide provides an example of a synthetic stream network generated using the processes described here.

Stream Link

- Assigns unique values to sections of a raster linear network between intersections





Input = Stream raster and flow direction grid

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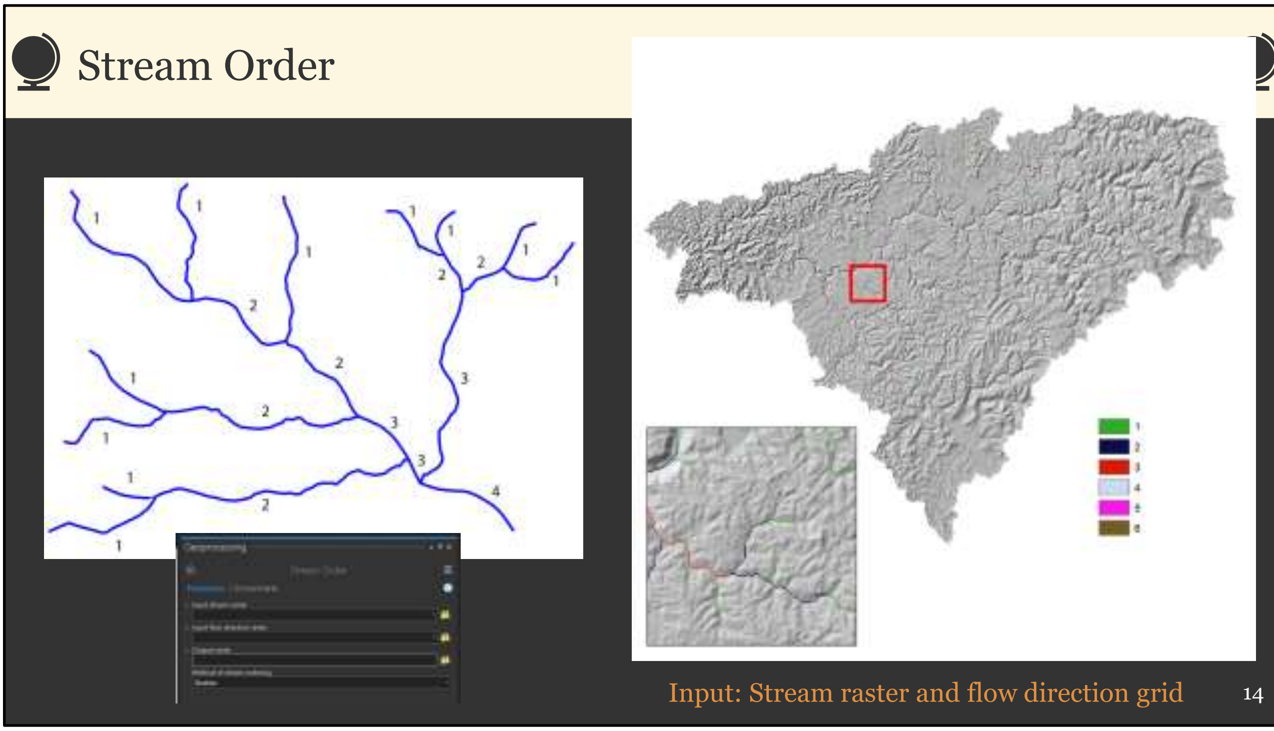
In a stream link grid, unique values are assigned to sections of a raster linear stream network.

Each section between intersections or confluences are assigned a unique value, as demonstrated in the provided example.

The required inputs are a stream raster grid and flow direction grid.



It is also possible to calculate stream order from stream raster grids and flow direction grids.

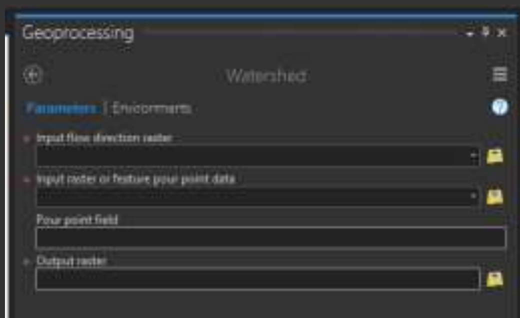
There are different methods for calculating stream order. Here, I will demonstrate the Strahler Method.

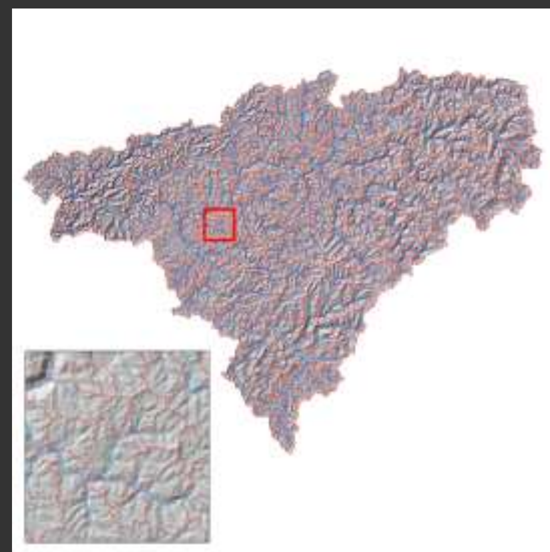
Using the Strahler Method, the smallest stream segments are labelled as 1st order streams. When two 1st order streams come together, a 2nd order stream is formed.

In order for a 3rd order stream to form, two 2nd order streams must come together. If a 1st and 2nd order stream come together, the result will still be a 2nd order stream.

Take some time to review the provided example and make sure you understand this concept.

Create your own Watersheds





Input = Flow direction raster and pour points (can use stream link grid)

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Using a flow direction grid and a stream link grid, it is possible to generate watersheds.

A drainage area will be calculated for each unique segment of the stream link grid.

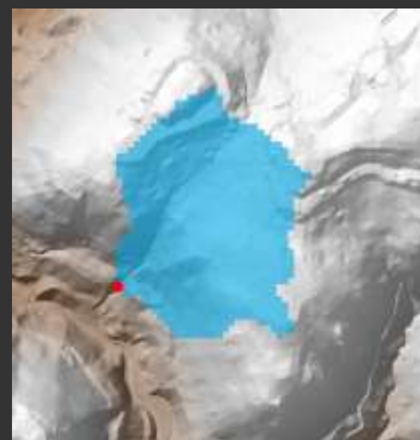
These areas will be assigned the same code as the stream segment to which they are associated.

Using this method, it is possible to generate watershed boundaries for an entire spatial extent.

The result will be a raster grid. Once it is generated, it is possible to convert the raster grid to polygons.

Catchment Areas for Pour Points

- Can define catchment areas for point locations
- Often you will need to snap the point to the largest flow accumulation cell within a search radius



Input = Flow direction raster and pour points (can use stream link grid)

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You can also calculate drainage areas associated with a specific point or location.

In this case, instead of producing watersheds for each unique stream segment, drainage areas will only be generated for the provided points.

When using pour points, they are commonly snapped or moved to the cell with the largest flow accumulation value within a defined extent.

This can be used to force the point to align with the synthetic stream network.

D8 vs. D-Infinity

Issues with D8 Method

1. Produce flow in parallel lines along principal directions (Moore, 1996)
2. Cannot represent adequate divergent flow over convex slopes and ridges (Freeman 1991)
3. Does not do well in highly variable topography with floodplains and wetlands (Liang and Mackay 2000)

❖ More robust methods, such as D-Infinity, are available

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The method described here is known as the D8 method. There are some issues with this method as described on this slide.

This method can produce flow in parallel lines along principal directions, it cannot represent adequate divergent flow over convex slopes and ridges, and it does not do well in highly variable topography with floodplains and wetlands.

There are more robust methods for calculating flow direction and flow accumulation, such as the D-Infinity method.

When using the D8 flow direction method, flow must be assigned to only one of the neighboring cells. With the D-Infinity method, it is possible to assign or partition flow to multiple cells.

Another Option: TauDEM

http://hydrology.usu.edu/taudem/taudem5/index.html

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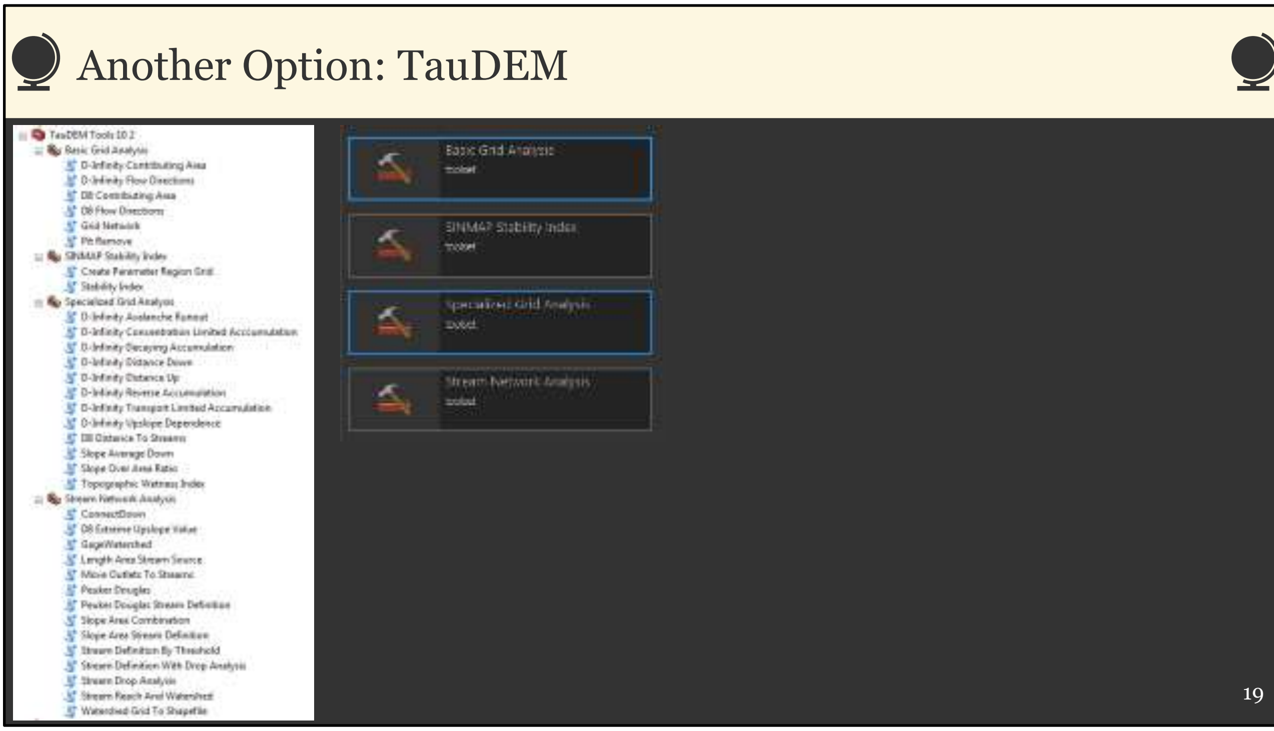
TauDEM, produced by David Tarboton at Utah State University, offers an alternative to the surface hydrologic modeling tools that are natively available in ArcGIS Pro.

This tool can be run as stand-alone scripts or using a toolbox in ArcGIS. There is also an associated R package.

If you are interested in surface water modeling, I highly recommend checking out this tool.



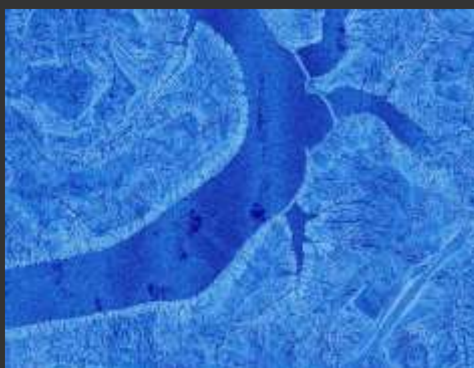
This slide shows the TauDEM toolbox made available for ArcGIS Pro.

Many tools are provided. Again, I highly recommend checking this out if you are interested in surface water modeling.

Compound Topographic Moisture Index (CTMI)

- Measure of steady state wetness as estimated from terrain characteristics

$$\ln\left(\frac{\text{(Upstream contibuting area)}}{\tan(\text{Slope})}\right)$$



Moore, I.D., P.E. Gessler, G.Z. Nielsen, and G.A. Petersen, 1993. *Terrain attributes: estimation methods and scale effects, Modeling Change in Environmental Systems* (A J. Jakeman, M.B. Beck, and M. McAleer, editors), Wiley, London, United Kingdom, pp. 189-214.

Gessler, P.E., I.D. Moore, N.J. McKenzie, and P.J. Ryan, 1995. Soil-landscape modelling and spatial prediction of soil attributes, *International Journal of Geographic Information Systems*, 9(4): 421-432.

A related measure is the compound topographic moisture index or CTMI.

This is a measure of steady state wetness based on terrain characteristics.

The equation is provided here.

Upstream contribution area is approximated using flow accumulation. Slope is calculated as topographic slope.

Wet cells will be those that have a large contributing area and a shallow slope. So, water enters but does not leave quickly.

In contrast, drier cells will be those that have a smaller contribution area and a steeper slope. So, not a lot of water enters the cell and water that does enter leaves quickly.

This can be a useful measure for estimating wetness or moisture on the landscape.

Some Issues with Modeling Surface Water Flow

A watershed is complicated

Lots of things impact surface runoff:

- Topography
- Geology
- Soils
- Antecedent soil moisture conditions
- Characteristics of the watershed
- Hydrologic modifications
- Watershed size, shape, orientation, etc.

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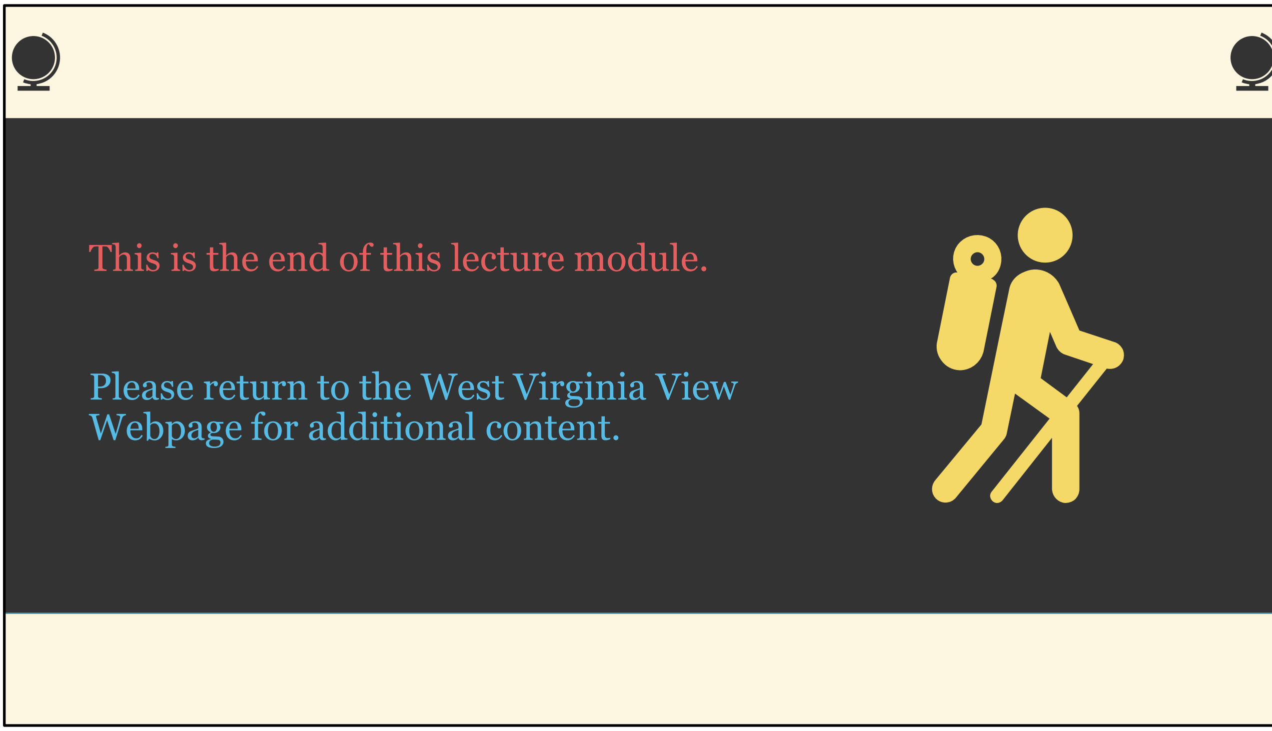
The surface hydrologic modeling methods described here are very useful. However, as with any modeling method, there are limitations.

For example, the amount of water in a stream or surface runoff is impacted by many factors including topography, geology, soil characteristics, antecedent soil moisture conditions (how saturated the soil was prior to a storm event), land cover conditions, amount of impervious surface, hydrologic modifications (such as dams), and watershed size, shape, and orientation.

However, these methods can still be of value. All models are wrong, but that doesn't mean that they aren't useful.



Thanks! Hope you found this useful.